Outgassing Measurement of the BTeV 5% Model of the Pixel Detector

C. Kendziora, M. Marinelli, M. Ruschman, M. Wong

21 June 2002

Abstract:

A model that is comprised of about 5% of the BTeV Pixel Detector has been built for the purpose of measuring its gas load due to outgassing. The vacuum chamber that is used for the gas load measurement has been built and calibrated. The calibration process is explained. After placing the model inside the vacuum chamber, the gas load due to the model's outgassing rate is measured, keeping the model at different temperatures.

1. Introduction:

A vacuum chamber has been built that will be used to measure the gas load of a model that is about 5% of the BTeV pixel detector. The method of the gas load measurement with the chamber has been described in a previous paper [1]. As seen in Figure 1, the vacuum chamber is divided into two regions by a rotating disk. The disk can be rotated to allow different pump speeds through different orifice sizes. Reading the pressure of chamber containing the turbo pumps and knowing the turbo pumping speed, we can determine the outgassing rate of the model at different temperatures. Another way to cross check the outgassing rate is to read the pressure-drop across the orifice and calculate the orifice conductance. The purpose of the paper is to explain the calibration method and the method to measure the outgassing rate. Paragraphs 2-3 describe the 5% model and the calibration system. Paragraphs 4-8 explain that the pump speed of the turbos is calculated from the orifice conductance and the ratio of pressures across the orifice. The pump speed in the turbo volume is calculated using a nitrogren leak and a helium leak. At Paragraphs 9-12, instead of a calibrated leak, the source of gas is the model itself. We use the calibrated apparatus to measure the outgassing rate of the model at different temperatures, the effect of the heat sink as a cryopump, and the outgassing rate of the empty chamber.

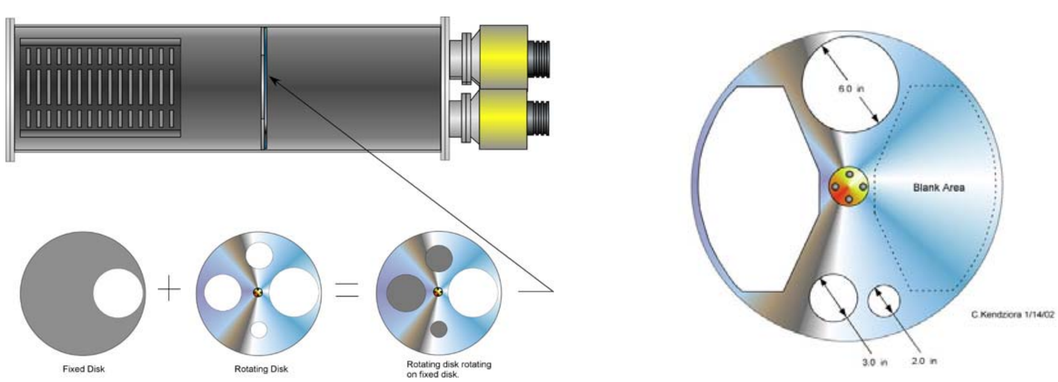

Figure 1 – Schematic of the Vacuum Chamber that Contains the 5% Model

2. Model Description:

The model, as shown in Figure 2, contains aluminum substrates that hold dummy chip assemblies, also called module assemblies. The six substrates hold about 10% of the total number module assemblies in pixel design. The module assemblies include dummy chips and kapton strips that were held together by 3M's Z-axis 5460R adhesive film. Stycast 2850FT epoxy (with the 24LV catalyst) was used to hold the module assemblies to the substrate. The substrates were held in place by carbon fiber brackets on a carbon fiber shell. An aluminum plate with slots cut out acted as both a heat sink and as a support for the ends of the kapton strips. The heat sink is held to the carbon shell at four places by stainless steel pins.

A cooling system had a tube running along the top and bottom of the edges of the heat sink, as shown in Figure 2. Another cooling system consists of tubes that run along the side of the substrates. For each substrate, the cooling tube is flattened and placed inside a channel that runs along the side.

The model did not include the electrical feedthrough boards or RF shield. For this reason, while the number of substrates was 10%, the model was estimated as 5% of the amount of material inside the vacuum system.

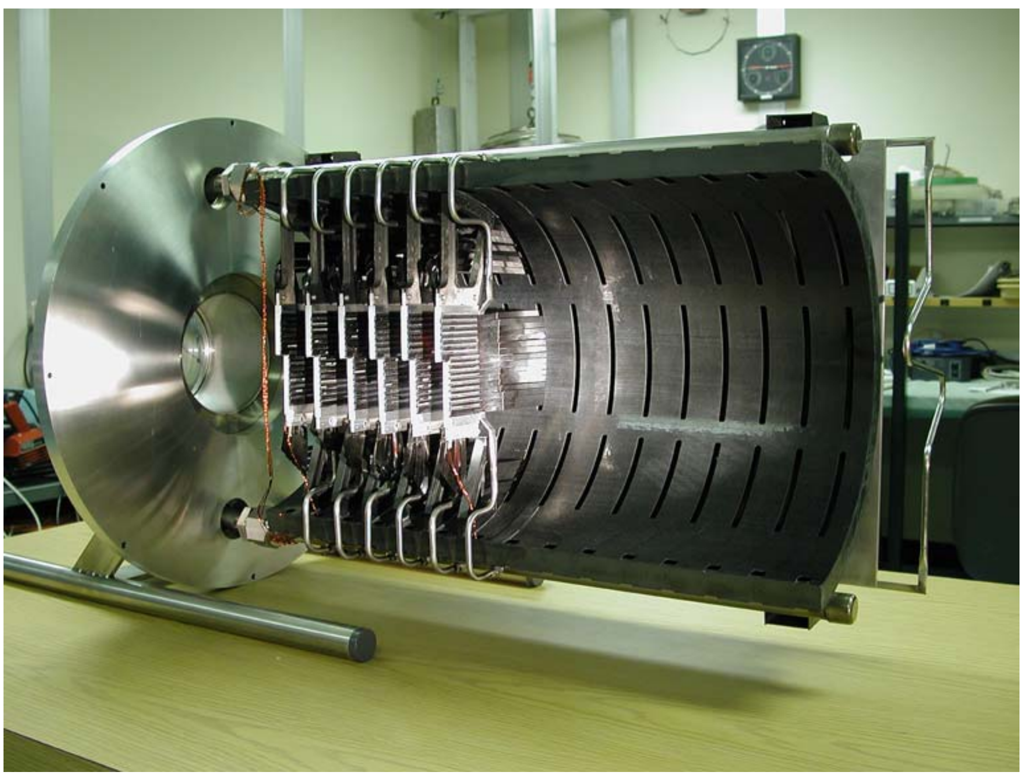

Figure 2 – 5% Model

3. Description of the Calibration System:

Figure 3 illustrates the calibration system for the vacuum chamber. The system allows flow of either helium or nitrogen. MV1 is a variable leak valve that allows different flow rates. The inlet pressure of the gas is shown at the absolute pressure gauge P_{gauge}. The manual valves MV2 and MV3 allow control of gas flow into the part of the vacuum chamber that holds the model and the part of the chamber next to the turbo pumps. The mass spectrometer leak detector is used as a cross check for measuring low flow rates. Three Leybold Turbovac turbomolecular pumps (model TMP 1000) are attached to the vaccum chamber and in parallel to each other. For this report, P_1 represents the pressure inside the volume that will hold the model. P_2 is the pressure of the volume where the turbo pumps are attached.

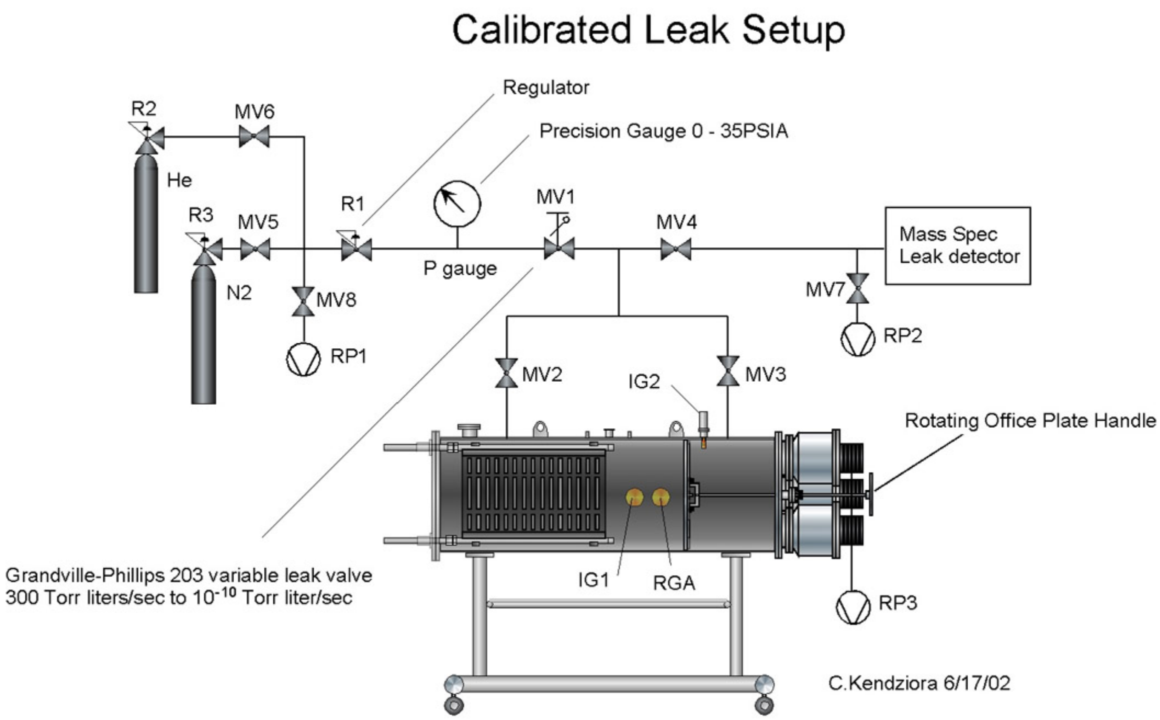

Figure 3 – Calibration System

4. Analysis Method:

The conductances of the orifice and the turbo pump speed are determined using the geometrical data and a constant pressure drop from a leak source. Since there is no flow meter in the system, the leak rate is not known. However, the conductance of the orifice is calculated based on its geometry. Next, a stable nitrogen leak is introduced into the volume that will hold the model. The orifice setting is at 2” opening. Once the chamber is in a steady state condition, the pressures P_1 and P_2 are recorded. The orifice setting is then changed to the combined 2”+3” openings. The pressures are recorded in steady state, where there is a constant throughput in the vacuum chamber. As an example for the 2-inch orifice:

$$Q_2 = C_2*(P_1 - P_2)_2 = S_T*P_2 \qquad (1)$$

where S_T = total pumping speed turbo volume
$(P_1 - P_2)_2$ = pressure difference across the 2-inch orifice

The equation can be written in terms of the ratio of pressures:

$$\frac{C_2}{S_T} = \frac{P_2}{(P_1 - P_2)_2} \qquad (2)$$

The ratio of pressures is written for the 2-inch plus 3-inch orifice:

$$\frac{C_{2+3}}{S_T} = \frac{P_2}{(P_1 - P_2)_{2+3}} \qquad (3)$$

The ratio of the conductances can also be written in terms of the ratio of pressures:

$$\frac{C_2}{C_{2+3}} = \frac{(P_1 - P_2)_{2+3}}{(P_1 - P_2)_2} \qquad (4)$$

This ratio of pressures is used to verify the calculation of the orifice conductances. The other two ratios of pressures are used to calculate the effective turbo pumping speed. The effective turbo pump speed is verified using the rating of the pumps provided by its manufacturer and the geometrical data. As a cross check, the analysis and the pressure measurements are repeated using a helium leak source.

5. Calculating the Conductance of the Orifice for Nitrogen:

The conductance of each orifice is calculated based on the orifice geometry. The thickness of the rotating plate is 0.5 inch. Thus calculating the conductance for nitrogen of the 2-inch diameter orifice as if it were a short tube:

C_2 = 11.6*a*A where a = 0.80
A = 20.3 cm^2

C_2 = 185 L/sec

Similarly for the 3-inch diameter orifice:

C_3 = 442 L/sec

Since the 3-inch diameter orifice is only used when in parallel with the 2-inch orifice, the combined conductance becomes:

$C_{2+3} = C_2 + C_3$
$C_{2+3} = 627$ L/sec

6. Verifying the Conductance of the Orifice Using Nitrogen:

To verify the conductance of each orifice, nitrogen is flowed through the calibration system into the vacuum chamber through MV2 (in Figure 3) for a given inlet pressure at P_{gauge} and opening for MV1 to control the flow rate. The pressures P_1 and P_2 are measured when the disk is rotated to the 2" orifice and the combined 2"+3" openings. Figure 4 shows the ratio of pressures for different flow rates using different gauge pressures. The consistency of the pressure ratio at different inlet pressures shows that the method of analysis is valid.

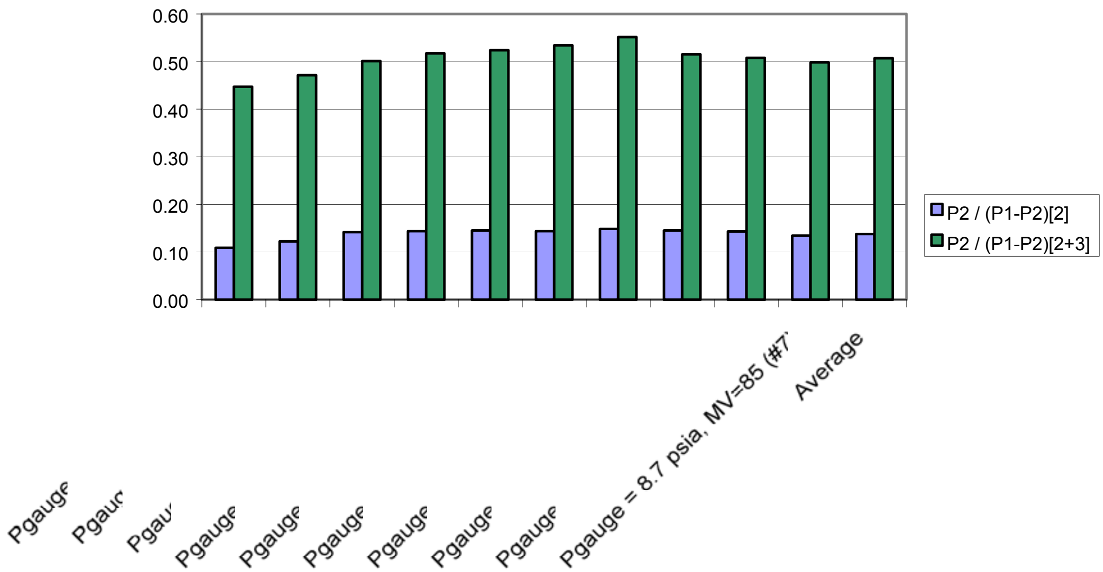

Figure 4 - Measured Ratio of Pressures

Figure 5 shows the ratio C_2 / C_{2+3} in terms of the measured pressures $(P_1 - P_2)_{2+3} / (P_1 - P_2)_2$. The ratio is compared to the calculated (theoretical) ratio C_2 / C_{2+3}.

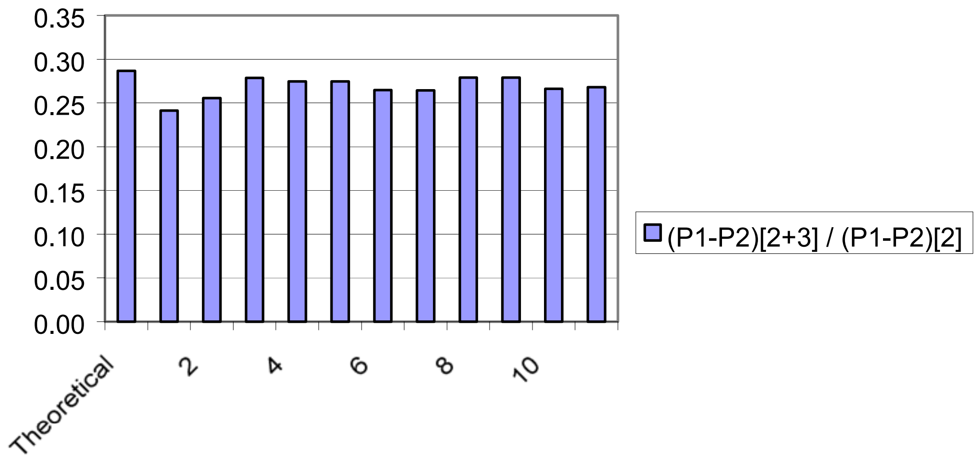

Figure 5 - Verifying the Ratio (P1-P2)[2+3] / (P1-P2)[2]

7. Calculating the total pump speed of the turbos:

The effective turbo pumping speed is calculated using the orifice conductance and the ratio of pressures by modifying equation 5:

$$S_T = \frac{C_2}{\left[\dfrac{P_2}{(P_1 - P_2)_2}\right]} = \frac{C_{2+3}}{\left[\dfrac{P_2}{(P_1 - P_2)_{2+3}}\right]} \qquad (5)$$

Figure 6 shows the total turbo pump speed for each measurement. The average of all data be the total turbo pumping speed S_T = 1300 L/sec for nitrogen.

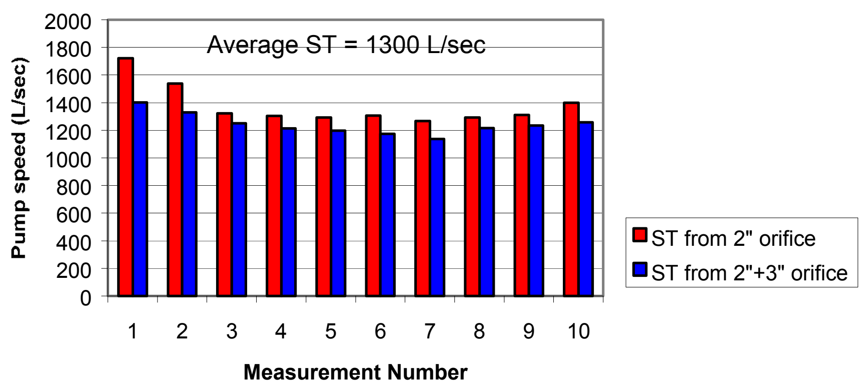

Figure 6 - Calculated Total Turbo Pump Speed for Nitrogen

Note that the rated pump speed for nitrogen for the TMP 1000 model is 850 L/sec. There are several factors that reduce the actual pump speed for the turbos. One factor is that each pump is attached to its own short, round tube that is then attached to the body of the vacuum chamber. The tube is 2.5-inches in length and 5.875 inches in diameter. The conductance of the tube in series with turbo pump speed reduces the effective pumping speed. Another factor that further reduces that total pumping speed is that the connecting tube is partially blocked by the wall of the vacuum chamber. Thus, due to the geometrical restraints for the turbo pumps, the value of the total pumping speed S_T = 1300 L/sec for nitrogen is reasonable.

8. Calibrating the vacuum chamber using helium

As a cross-check to the calibration procedure and calculations, the conductance of the orifice is calculated and measured with helium flowing through the calibration system. The conductance of the tube connecting the turbo pump to the vacuum chamber must be calculated for helium. The equation for tube conductance for a gas, dubbed Gas A, is

$$C_{tube\text{-}A} = \nu_A * K \qquad (6)$$

where ν_A = average velocity of particles in Gas A
K = constant that is a function of the tube geometry

The average molecular velocity is a function of temperature and molecular mass:

$$\nu_A = \sqrt{\frac{8 * k * T}{\pi * m_A}} \qquad (7)$$

where k = Boltzman constant
T = gas temperature
m_A = molecular mass of Gas A

The conductance of Gas B through the same tube can be written as the ratio of the square roots of the molecular mass of each gas times the tube conductance of Gas A:

$$C_{tube-B} = C_{tube-A}\sqrt{\frac{m_A}{m_B}} \qquad (8)$$

The molecular mass of nitrogen is m_{N2} = 28 and the mass of helium is m_{He} = 4. Thus, the conductances of the orifices can be calculated using the orifice conductance for nitrogen and the ratio of molecular masses:

$C_{2\text{-}He}$ = 490 L/sec
$C_{3\text{-}He}$ = 1170 L/sec

$C_{2\text{-He}} + C_{3\text{-He}} = 1660$ L/sec

Figure 7 shows the ratio of pressures taken from the vacuum chamber when helium was flowing through the calibration system.

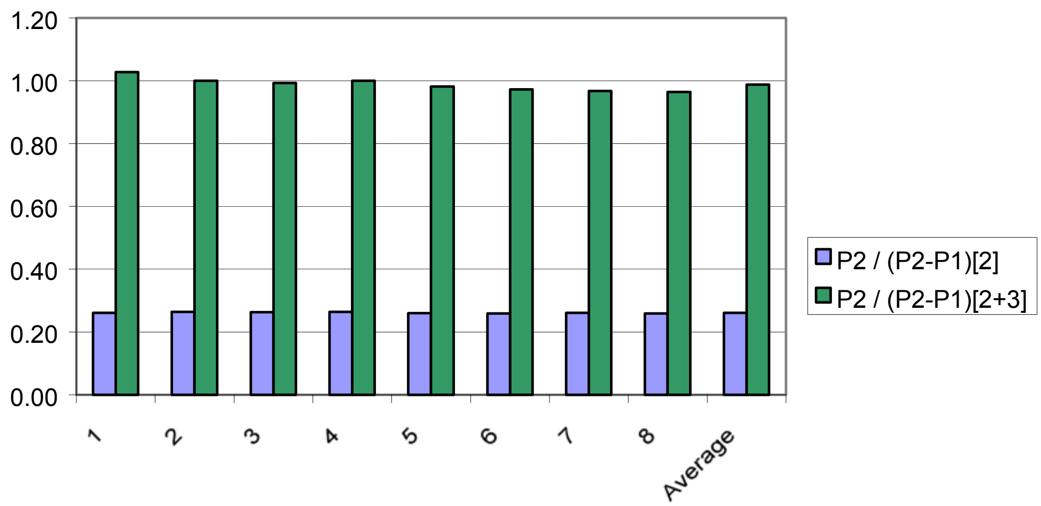

Figure 7 - Ratio of Measured Pressures using Helium

Figure 8 shows the ratio C_2 / C_{2+3} in terms of the measured pressures $(P_1 - P_2)_{2+3}$ / $(P_1 - P_2)_2$ and compares the ratio to the calculated ratio $C_2 / C_{2+3} = 490 / 1660 = 0.295$. Note that this ratio should not and does not depend on the gas molecular mass.

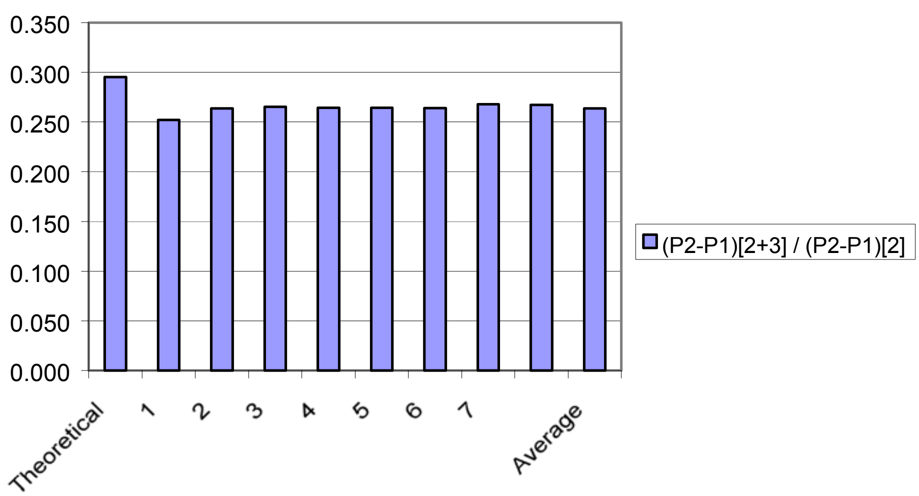

Figure 8 - Verifying the Ratio (P2-P1)[2+3] / (P2-P1)[2] for Helium

Figure 9 shows the effective helium turbo pump speed calculated from the orifice conductance and the ratio of pressures. The average total pump speed for helium based on the data is $S_{T\text{-}He}$ = 1780 L/sec. It is noted that while the manufacturer's rated pump speed for each turbo is 880 L/sec for helium, the geometrical constraints reduce the effective pump speed in the same way as for nitrogen so that the effective pump speed $S_{T\text{-}He}$ is not more than 1800 L/sec.

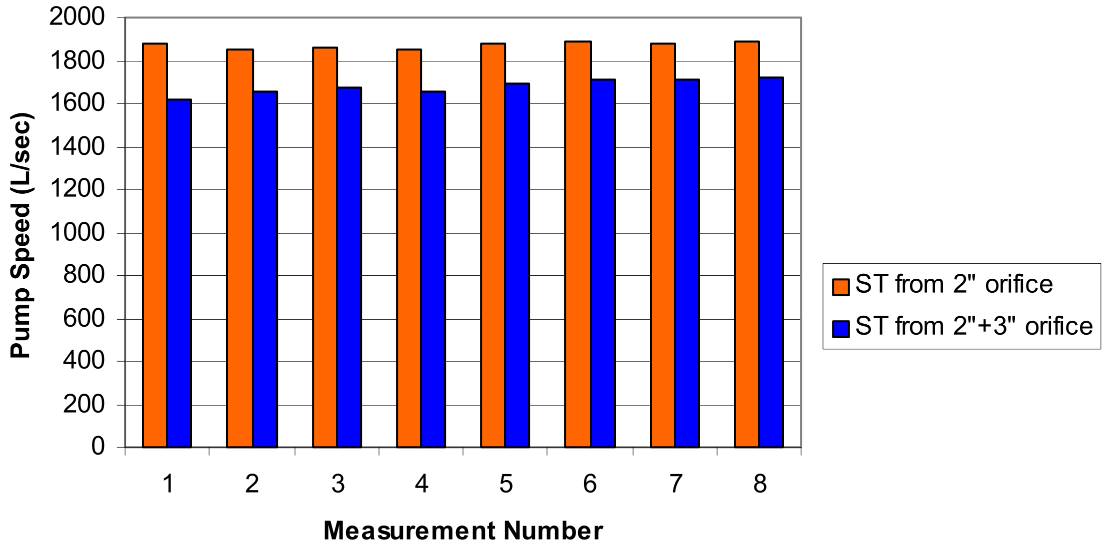

Figure 9 - Helium Turbo Pump Speed Based on Measured Pressures

Average ST = 1780 L/sec

Table 1 summarizes the conductances of the orifice and the total turbo pumping speed that was obtained during the calibration process.

Table 1 – Values Obtained from Calibration Process

	Nitrogen	Helium
C_2 (L/sec)	200	500
C_3 (L/sec)	400	1200
C_{2+3} (L/sec)	600	1700
S_T (L/sec)	1300	1800

9. Calculating the conductance of the orifice using water:

Since the majority of gas that is expected to outgas from the pixel detector model is water, the pump speed and orifice conductances are calculated for water too.

The orifice conductance is calculated for water using the ratio of molecular masses:

$C_{2\text{-}H2O}$ = 230 L/sec
$C_{3\text{-}H2O}$ = 550 L/sec
$C_{(2+3)\text{-}H2O}$ = 780 L/sec

As mentioned before, the total turbo pumping speed for nitrogen is a function of the speed of the pump itself and the conductance of the connecting tube. This can be written mathematically and the conductance of a single tube solved:

$$\frac{1}{S_T} = \frac{1}{3}\left(\frac{1}{S_{pump}} + \frac{1}{C_{tube}}\right) \tag{9}$$
$$C_{tube} = 884 \ \text{L/sec}$$

where S_T = 1300 L/sec
S_{pump} = 850 L/sec

The conductance of the tube for water can be calculated using equation [], knowing that the molecular mass of water m_{H2O} = 18:

$$C_{tube-H2O} = C_{tube}\sqrt{\frac{m_{N2}}{m_{H2O}}} \tag{10}$$
$$C_{tube-H2O} = 1103 \ \text{L/sec}$$

According to the manufacturer's specifications, the rated pump speed for water is $S_{pump\text{-}H2O}$ = 850 L/sec. So, the total turbo pump speed seen by the vacuum chamber is calculated:

$$\frac{1}{S_{T-H2O}} = \frac{1}{3}\left(\frac{1}{S_{pump-H2O}} + \frac{1}{C_{tube-H2O}}\right) \tag{11}$$
$$C_{tube-H2O} = 1440 \ \text{L/sec}$$

<u>10. Outgassing Rate of the Model:</u>

Now, with the model inside the vacuum chamber, the gas source is the model, as shown in Figure 10. From the RGA readings, water is the major source of gas. Knowing the effective turbo pump speed of water $S_{T\text{-}H2O}$ = 1400 L/sec and the pressure measurements of the turbo volume, one can calculate the outgassing rate as shown in Equation 12. The pressure measurement is adjusted to account for the ion gauge sensitivity for water, which is 0.9.

$$Q_{model} = \frac{P_2}{0.9} * S_{T-H2O} \tag{12}$$

Figure 10 – Placing the Model Inside the Vacuum Chamber

Figure 11 shows the gas load Q of the 5% pixel detector model inside the vacuum chamber at room temperature. The pressure measurements are taken when the orifice is set at the largest opening. Taking into account that the model is approximately 5% of the total detector, the expectant gas load of the entire detector is 0.01 torr-L/sec.

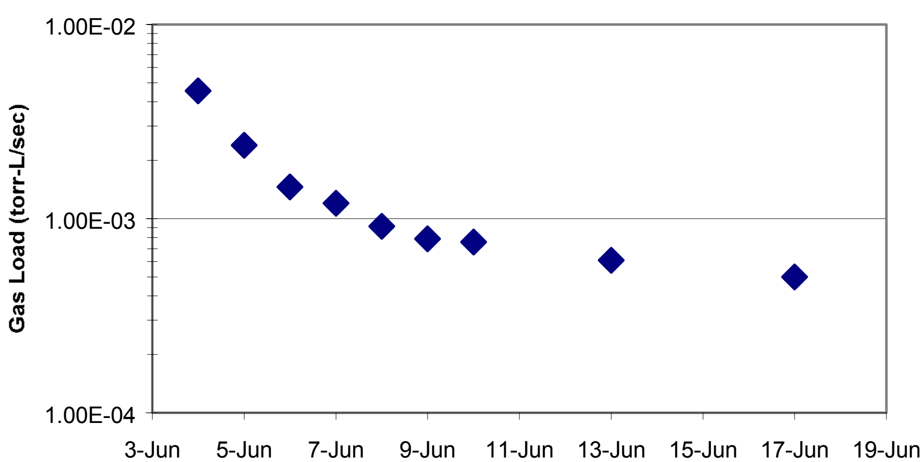

Figure 11 - Gas Load of Model at Room Temperature

As a cross-check, the gas load of the model can be calculated using an orifice conductance and the pressure difference across it:

$$Q = C_2 * (P_1\text{-}P_2)_2 = S_T * P_2$$

As an example, for June 17, the pressure difference across the 2-inch orifice was (2.1e-6 – 3.4e-7) torr = 1.8e-6 torr. As shown in Section 9, the conductance through the 2-inch orifice is 230 L/sec. As a result, the gas load is Q_{model} = 4e-4 torr-L/sec.

Once measurements were taken of the model at room temperature, water glycol was allowed to flow into the cooling manifold for the substrate and the cooling tube for the heat sink. The water glycol brought the temperature of the substrates and the heat sink down to about –10ºC. Pressure measurements were recorded throughout the day when the rotating plate was set at various orifice sizes.

After all measurements were recorded, the water glycol was drained from the heat sink cooling tube. Nitrogen gas then flowed through the tube. After, the tube was pumped to remove the water glycol. Once the cooling tube was dry, flow of liquid nitrogen took place through only the heat sink. Once it flowed past the heat sink, the liquid nitrogen vented to atmosphere. The temperature of the heat sink was approximately -160ºC. Measurements were taken when the substrates remained at around 20ºC.

For the next set of measurements, the substrates were cooled to –10ºC by flowing cold water glycol through the cooling tubes. Liquid nitrogen continued to flow past the heat sink.

Table 2 shows the pressure measurements when the substrates and the heat sink were at various temperatures. The RGA readings are in arbitrary units and used where the ratios are important. Note that when the substrates and model were cooled to –10ºC , the gas load was subsequently reduced by a factor of two from when the items were at room temperature.

When the heat sink acts as a cryopump near liquid nitrogen temperature, the water partial pressure does not change when the orifice conductance is lowered. However, the nitrogen partial pressure is affected. This is shown by rotating the orifice at different settings and noting the RGA readings for water and nitrogen.

Table 2 – Pressure Measurements, Gas Load, and RGA Readings when Substrate and Heat Sink Were Cooled

Substrate Temp	Heat Sink Temp	Orifice setting	P1 (torr)	P2 (torr)	Q (torr-L/sec)	RGA H2O reading	RGA N2 reading
20ºC	20ºC	Large	3.40E-07	3.40E-07	5.20E-04	**4.80E-08**	5.00E-10
		2”	2.08E-06	3.36E-07		**3.20E-07**	2.90E-09
-10ºC	-10ºC	Large	1.70E-07	1.60E-07	2.60E-04	3.50E-08	
		2”	1.10E-06	1.60E-07		1.80E-07	
20ºC	-160ºC	Large	1.26E-08	1.86E-08			
		2”	2.07E-08	1.63E-08		1.00E-09	
-10ºC	-160ºC	Large	1.04E-08	1.08E-08		**7.20E-10**	1.00E-10
		2”	1.62E-08	7.40E-09		**7.90E-10**	5.30E-10
		Blank	1.20E-07	5.90E-09		**9.70E-10**	1.00E-08
		Large	9.20E-09	8.70E-09			

11. Calculating the pump speed of the cryopump

The pump speed of the heat sink as a cryopump can be calculated based on the RGA readings of water and nitrogen. Note in Table 2 that the RGA reading of nitrogen reduces by a factor of five between heat sink temperatures 20ºC and -160ºC. The reason for the reduction is that the lower temperature is reducing the nitrogen outgassing rate. Assume, then, that the outgassing rate for water is reduced in the same amount. Thus, the RGA reading of water would drop from 4.80E-8 to 9.60E-9 when the heat sink temperature changes from 20ºC and -160ºC. However, the RGA reading is at a lower amount of 7.20E-10. The reason for the further reduction is that the cryopump is pumping the additional water. The reduction of water from 9.60E-9 to 7.20E-10 due to the cryopump is a factor of 13. The cryopump speed of water must then be 13 times the turbo pump speed of water. The calculated turbo pump speed for water is 1400 L/sec. Thus, the cryopump speed is calculated as 19,000 L/sec.

As a cross-check on the pump speed of the cryopump, assume the specific pump speed of a cryopump, assuming a sticking coefficient of 1, is about 10 L/sec-cm^2. The dimensions of the face of the heat sink is approximately 25 by 13-inches. Looking at Figure 2, the panel cannot pump water on both sides due to a geometrical constraint on one side, namely the close proximity of the carbon fiber support shell. Assuming that only one side of the panel acts as a pump, the total surface area that acts as a cryopump is approximately 2000 cm^2. That results in a pump speed of 20,000 L/sec. This shows that the cryopump speed based on the RGA readings is reasonable.

12. Outgassing rate of the empty vacuum chamber:

The outgassing rate inside the empty chamber can be calculated based on the pressure measurements and the turbo pump speed for nitrogen. The RGA reading showed that the major source of gas in the empty chamber was nitrogen. The average gas load of the empty stainless steel vacuum chamber based on pressure measurements is 1.8e-5 torr-L/sec. With the turbo pump chamber having a length of 22-inches and diameter 19.5-inches, the average specific outgassing rate is 1.0e-10 torr-L/sec-cm^2. Research on past specific outgassing rates of fresh, untreated stainless steel ranges from 1.35e-5 to 2.1e-4 torr-L/sec-m^2. This equals 1.35e-10 to 2.1e-9 torr-L/sec-cm^2.

13. Summary

The vacuum chamber that was built for the 5% model worked well. The pump speed of the turbo was well understood for nitrogen, helium and water. The conductances and the pumping speed in Table 3 are known. The results and the pressure measurement are used to calculate the outgas rate for the empty chamber and for the model.

Table 3 – Orifice Conductances and Total Turbo Pump Speed

	Nitrogen	Helium	Water
C_2 (L/sec)	200	500	200
C_3 (L/sec)	400	1200	600
C_{2+3} (L/sec)	600	1700	800
S_T (L/sec)	1300	1800	1400

The gas load of the 5% model at room temperature was measured to be 5e-4 torr-L/sec. Thus, the expectant pixel detector gas load is 0.01 torr-L/sec, which is the same as the calculated gas load based on research of the literature of material outgassing rates. When the model and the heat sink were cooled to -10ºC using water glycol, the gas load of the model was reduced by a factor of two compared to the gas load when the model and heat sink at room temperature. When liquid nitrogen was introduced into the heat sink, the lowered temperature resulted in the heat sink acting as a cryopump. The cryopump dominated the pumping of water, having a pump speed of 19,000 L/sec.

It was observed that while the heat sink was cooled to -160ºC, the outside wall was at room temperature. Applying the results of the model measurements to the design of the BTeV pixel detector, adding a cryopump gives a pressure better than the required 1e-7 torr. Having a cyropump removes the necessity of splitting the vacuum chamber into two separate vacuum regions.

References:

1. Howell, et al, "Analysis of the BTeV Vertex Vacuum System," BTeV Database Document 318, November, 2001.
2. O'Hanlon, A User's Guide to Vacuum Technology, Second Edition, John Wiley & Sons, 1976.
3. Wong, "Review of papers regarding vacuum system and materials," http://home.fnal.gov/~mlwong/outgas_rev.htm, 2001.